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13. ABSTRACT (Maximum 200 words)  This comprehensive study has examined the key effects of sliding friction in spur and helical gear dynamic models, vibro-acoustic sources and geared system responses. First, many dynamic phenomena that emerge due to the interactions between time-varying mesh stiffness, sliding friction and/or surface finish are successfully formulated. Second, new multi-degree-of-freedom models considering both torsional and translational dynamics of spur and helical gear pairs have been developed. These include time-varying mesh stiffness, sliding friction excitation and shaft/bearing compliances. Line-of-action and off-line-of-action motion predictions, based on the lumped gear dynamic models, match well with a benchmark finite element/contact mechanics code. Third, new mathematical models have been proposed to examine structure-borne and air-borne noise that should arise due to surface asperities as a function of operating speed and surface finish. Fourth, mobility type frequency response studies of the system vibro-acoustic characteristics provide new insights into dynamic forces at the bearings and sound radiation. Fifth, two sets of experimental studies at ARL/NASA Glenn were conducted. Gear noise source and lumped system models match well with experiments on ARL/NASA spur gears. Finally, a set of helical gears has been designed that clearly isolate the effects of sliding friction. Suggestions for future research are included.				
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## **Final Progress Report**

# **DYNAMIC ANALYSIS OF SLIDING FRICTION IN ROTORCRAFT GEARED SYSTEMS**

Grant Proposal Number 42571-EG [ARO Award # DAAD19-02-1-0334]

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### **(1) Foreword (optional)**

None

### **(2) Statement of the problem studied**

This comprehensive study has examined the key effects of sliding friction in spur and helical gear dynamic models, vibro-acoustic sources and geared system responses. First, many dynamic phenomena that emerge due to the interactions between time-varying mesh stiffness, sliding friction and/or surface finish are successfully formulated. Second, new multi-degree-of-freedom models considering both torsional and translational dynamics of spur and helical gear pairs have been developed. These include time-varying mesh stiffness, sliding friction excitation and shaft/bearing compliances. Line-of-action and off-line-of-action motion predictions, based on the lumped gear dynamic models, match well with a benchmark finite element/contact mechanics code. Third, new mathematical models have been proposed to examine structure-borne and air-borne noise that should arise due to surface asperities as a function of operating speed and surface finish. Fourth, mobility type frequency response studies of the vibro-acoustic characteristics of the geared system provide new insights into the dynamic forces at the bearings and sound radiation. Fifth, two sets of experimental studies at ARL/NASA Glenn were conducted. Gear noise source and lumped system models match well with experiments on ARL/NASA spur gears. Finally, a set of helical gears has been designed that clearly isolate the effects of sliding friction. Suggestions for future research are included.

### **(3) Summary of the most important results**

Sliding friction between the gear teeth is considered to be a key source of excitation for structure borne noise in rotorcraft drivetrain applications. The primary focus of this research is to study the role of sliding friction in the dynamic response of gears through computational, analytical and experimental approaches. Refer to Table 1 for an overview of the research objectives and important results.

Table 1. Summary of gear dynamics research with focus on sliding friction

Research Task(s) Accomplished	Spur Gear	Helical Gear
Example cases examined	1. NASA set (unity ratio) 2. NASA-ART gear (non-unit ratio)	1. NASA/ART set 2. Automotive set
Linear Time-Invariant (LTI) system analysis of gear system (with sliding friction)	Yes	No
Linear Time-Varying (LTV) system analysis of gear system (with sliding friction)	Yes	Yes
Experimental studies conducted (running experiments; transfer functions)	Yes	Yes
Validation of selected models	- Using CALYX* - Using experiments at ARL/NASA Glenn	- Using CALYX * (static case only)
Modeling of structure-borne and air-borne noise induced surface finish	Yes	No
Design issues examined (bearing force minimization; isolation of sources, etc.)	Yes	Yes

Key \*: finite element/contact mechanics code

Key accomplishments include the following; refer to the detailed final report for details.

3A. Developed new multi-degree-of-freedom (MDOF) lumped system models for the spur and helical gear pairs that include time-varying system parameters, friction excitations and shaft/bearing compliances. Analysis has shown that when the film thickness is less than the surface roughness, mixed lubrication occurs and surface characteristics should be considered. Under mixed lubrication, the average coefficient of friction value depends on surface roughness and lubrication conditions. Sliding friction has the most significant effect on the off-line-of-action direction dynamics and its relative contribution is case dependant. For high precision gears with small manufacturing errors, sliding friction is a significant contributor to gear vibration and it becomes increasingly important at higher loads.

3B. Developed a new noise source model from gear surface roughness and examined the relationship of the gear noise from surface asperities as a function of operating speed and surface roughness. The new analytical model describes gear tooth surface undulations (surface finish) using the wave number domain concept. Sinusoidal surface variations are incorporated into a simple torsional gear pair system. Preliminary results show that surface undulations can amplify the gear mesh harmonics, excite non-gear mesh harmonic frequencies (such as the ghost frequencies), induce a broadband excitation and give rise to some modulation sidebands.

3C. Two separate experimental studies have been undertaken to identify the relative importance of sliding friction in gear noise excitation. First, experimental studies on a spur gear were conducted at the ARL/NASA Glenn Research Center. A new anechoic chamber has been added to the gear noise rig to facilitate isolated and directly radiated sound measurements. A matrix of noise and vibration data has been acquired over a range of torques, lubrication temperatures, and gear surface finishes. Second, a preliminary experiment on helical gears was conducted at OSU.

3D. Developed a linear time-invariant (LTI) model including sliding friction for a simplified geared system with 8 DOF using the mobility analysis/synthesis method. This model describes the dynamics of the NASA gear noise rig in the frequency domain. Some controlled experiments were conducted to derive the frequency response functions of the geared system. Chief motivation of system level analysis is to understand the coupling between sliding friction and transmission error (TE) excited response and rank order for the relative importance of gear sources in generating structure-borne noise.

3E. Validated the MDOF lumped spur gear pair model using comparative experiments based on NASA unity ratio spur gear pair. Predictions match well for both line-of-action and off-line-of-action motions for the dominant gear mesh harmonics. Further, sound pressure prediction (under the influence of two vibration sources) match well with measured data. The role of tip relief is also clarified in the presence of sliding friction.

3F. Designed a set of gears that first maximize transmission error and shuttling forces separately while minimizing other excitations, and then one design with minimal excitations (from all sources). These will be fabricated by the Ford Motor Company for this project; experimental plans are also under way.

Our comprehensive study aims to incorporate various aspects of sliding friction in the gear dynamic models and vibro-acoustic control schemes. Many dynamic phenomena that emerge due to interactions between parametric (stiffness) variations, frictional effects, and surface topography (surface finish) are predicted. Our findings are expected to greatly enhance the current state-of-the-art in gearbox noise and vibration and lead to improved design guidelines and simulation tools that will benefit the Army Research Labs and the rotorcraft industry in general.

**(4) Listing of all publications and technical reports supported under this grant or contract. Provide the list with the following breakout, and in standard format showing authors, title, journal, issue, and date.**

(a) Papers published in peer-reviewed journals

N/A

(b) Papers published in non-peer-reviewed journals or in conference proceedings

Gunda, R. and Singh, R., 2003, "Dynamic Analysis of Sliding Friction in a Gear Pair," Proceedings of ASME Design Engineering Technical Conferences, paper # DETC 2003/PTG-48055, Sept. 2003, Chicago, IL.

(c) Papers presented at meetings, but not published in conference proceedings

N/A

(d) Manuscripts submitted, but not published

N/A

(e) Technical reports submitted to ARO

Singh, R., 2004, Interim Technical Report, “Dynamic Analysis of Sliding Friction in Rotorcraft Geared Systems,” submitted to the ARO in August 2004.

Singh, R., 2005, Final Technical Report, “Dynamic Analysis of Sliding Friction in Rotorcraft Geared Systems,” submitted to the ARO in September 2005 (360 pages).

(f) Papers in preparation

The following papers are being written for submission to international journals. Titles are subject to change. Also, each paper could be presented (in a summarized form) to national or international meetings or conferences such as the ASME Power transmission and Gearing and the SAE Noise and Vibration Conferences. First 3 papers in the list given below will be submitted by November 2005. Remaining articles will be written in winter 2006.

“Dynamics of MDOF Spur Gear Pair System with Realistic Time-Varying Stiffness Functions in the Presence of Sliding Friction,” by S. He, R. Gunda and R. Singh, in preparation for the Journal of Sound and Vibration. (Based on sections 3, 6, 8 of the Final Technical Report)

“Dynamic Formulation of Helical Gear Pair Model in the Presence of Sliding Friction and Stiffness Variations,” by S. He, R. Gunda and R. Singh, in preparation for the Journal of Sound and Vibration. (Based on section 4 of the Final Technical Report)

“Gear Surface Roughness Induced Airborne Noise Source, based on a Linear Time-Varying Model,” by S. Kim and R. Singh, in preparation for the Journal of Sound and Vibration. (Based on section 5 of the Final Technical Report)

“Vibro-Acoustics of a Spur Gear System with Transmission Error and Sliding Friction Excitations: Part I – Experimental and Computational Studies,” by V. Asnani, A. Holub, S. He, and R. Singh, in preparation for the Applied Acoustics Journal or the Noise Control Engineering Journal. (Based on sections 6, 7 and 8 of the Final Technical Report)

“Vibro-Acoustics of a Spur Gear System with Transmission Error and Sliding Friction Excitations: Part II - Mobility Analysis,” by A. Holub, V. Asnani, S. He, and R. Singh, in preparation for the Applied Acoustics Journal or the Noise Control Engineering Journal. (Based on sections 6, 7 and 8 of the Final Technical Report)

## **(5) Technology Transfer**

5A. Conferred with the ARL/NASA Glenn and Sikorsky Aircraft Corp. researchers and prepared a collaborative project proposal that was submitted to the Rotorcraft Industry Technology Association (RITA) and National Rotorcraft Technology Center (NRTC): “Analysis of Gear Noise Sources Controlled by Sliding Friction and Surface Roughness” (WBS No. 04-B-07-01.3-A18). Principal Investigator: Rajendra Singh (The Ohio State University). Collaborators: Dr. Harsh Vinayak (Drive Systems, Sikorsky Aircraft

Corporation – he resigned from Sikorsky in late 2004) and Dr. Timothy L. Krantz (Army Research Laboratory, NASA Glenn Research Center). Budget: \$55K (2004), \$40K (2005) and \$130K (2006). This project (in collaboration with ARL/NASA Glenn and Sikorsky) intended to focus on experimental issues and on the modeling of gear surface finish induced sources. However, no funds have been received thus far by the Ohio State University (*due to a lack of agreement regarding the intellectual property rights*) though some funds were transferred to NASA Glenn for experiential work by one OSU student. These efforts (including the RITA/NRTC project) would ensure an effective transfer of the analytical methods that have been generated under the ARO project.

5B. Analytical models of a spur gear pair were created based on ARL/NASA and NASA\_ART gear geometry. This model was validated using finite elements with the added benefit of being suitable for parametric studies and less computation time. Analysis shows sliding friction to be the source of critical bearing oscillations in the off-line-of-action direction and to increase the higher harmonics of the dynamic transmission error.

5C. Experiments have been conducted at OSU and ARL/NASA Glenn, and several gears with isolated excitations are being fabricated for future tests.

5D. Presentations made at the Ohio State University Gear Lab. Industrial Sponsor's Meetings: in June 2003 and Jan. 2005. The ARL staff (at NASA Glenn) and approximately 35 companies (including the rotorcraft companies) active in gear analysis and design have attended these meetings.

5E. The computer simulation tools (based on our lumped system models and analytical solution techniques) will be made available for transfer to ARL/NASA Glenn and Army helicopter contractors, upon request.

5F. Also, informal discussions with the Ford Motor Company have taken place regarding the fabrication of new gear sets (with isolated excitations) and experimental plans.

**(6) List of all participating scientific personnel showing any advanced degrees earned by them while employed on the project**

**6A. Graduate Students**

Tom Schachinger (MS student) -- MS Degree awarded in Autumn 2004) -- currently with Exxon Mobil

Allison Holub (MS student) -- MS Degree awarded in Summer 2005 – currently with General Electric

Song He (PhD student) -- PhD degree expected in 2007

Vivake Asnani (MS student) -- MS degree expected in Autumn 2005

**6B. Post-Doctoral Researchers**

Dr. Seungbo Kim (Post-doctoral researcher) – currently with Goodyear Technical Center

Dr. Rajendra Gunda (Post-doctoral researcher) – currently with ANSOL

Dr. Hyeongill Lee (Post-doctoral researcher) – currently with Samsung

**(7) Report of Inventions (by title only)**

N/A

**(8) Bibliography**

Refer to the Final technical Report (by. R. Singh, Sept. 2005) for a comprehensive listing. Overall, 85 articles, books, papers or analysis codes are cited.

**(9) Appendix**

None